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Randall L. Jensen · Patty S. Freedson · Joseph Hamill

The prediction of power and efficiency during near-maximal rowing

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Abstract The relationship between power and gross efficiency during near-maximal rowing, and physiological measures of strength, power, aerobic and anaerobic capacities and United State Rowing Association (USRA) performance tests (independent variables) was investigated among collegiate male rowers. Criterion measures of rowing power and gross efficiency were measured in a moving-water rowing tank, using an oar instrumented with strain gauges to assess force and a potentiometer to assess oar position. Bivariate correlation analysis ($n = 28$) indicated no relationship between the independent variables and rowing gross efficiency ($P > 0.05$). Rowing power [mean (SD) 483.4 (34.75) W] was significantly related to inboard leg extension strength (IL strength, $r = 0.63$), outboard leg extension strength ($r = 0.45$), combined leg extension strength ($r = 0.45$), and time to complete the USRA 2000-m simulated rowing race ($r = -0.52$; $P < 0.05$). Stepwise regression using resampling cross-validation of 15 random samples (21 subjects per sample selected from a total group of 28 intercollegiate oarsmen) indicated that predictors of rowing power were IL strength and blood lactate following a peak oxygen uptake rowing test with significant multiple correlations of $R = 0.61$ to 0.86 ($P < 0.05$). The standard error of estimate (SEM) ranged from 18.1 to 29.9 W, or 5.3 (0.77)% of the criterion value. Cross-validation with a hold-out group (seven subjects per sample) was performed for each equation and correlations ranged from $R = 0.14$ to 0.97 (SEM = 8.0 to 38.9 W). In conclusion, data from the present study suggest that to increase rowing power, training should emphasize leg strength and anaerobic training to decrease the level of lactate accumulated during rowing.

Key words Energy cost · Anaerobic energy · Tank rowing · Muscular strength · Blood lactate ·

Introduction

The determination of gross efficiency during physical activity requires the measurement of energy cost to perform sustained work (Cavanagh and Kram 1985). The cost is usually measured below the onset of blood lactate accumulation and includes only energy transformed in the aerobic metabolic pathway (Gladden and Welch 1978). However, many types of competitive activities are performed at intensity levels requiring high degrees of aerobic and anaerobic energy metabolism (Åstrand and Rodahl 1986). The sport of rowing is an excellent example, because the energy demands of a 2000-m race are approximately 67% aerobic and 33% anaerobic (Steinacker 1993). Therefore, if gross efficiency is determined at near-maximal intensities, anaerobic energy metabolism should be included in the total energy cost.

An alternative to determining gross efficiency would be to establish the mechanical power that can be sustained during an activity. The athlete who can sustain the highest mechanical power throughout the event should be the first to the finish line. Sustained mechanical power is equivalent to the numerator of efficiency without requiring the establishment of energy cost. The comparison of sustained mechanical power levels would avoid difficulties in quantifying anaerobic energy cost required during high-intensity exercise.

The prediction of either rowing efficiency or sustained mechanical power should allow determination of the variables that affect rowing performance. Therefore,

R.L. Jensen (✉)
Department of Kinesiology, Health Promotion, and Recreation, P.O. Box 13857, University of North Texas, Denton, TX 76203, USA

P.S. Freedson · J. Hamill
Department of Exercise Science,
University of Massachusetts-Amherst, Amherst, MA 01003, USA

the purpose of the current investigation was to predict near-maximal rowing mechanical power and gross efficiency from strength, power, aerobic and anaerobic capacities, and measures of rowing performance.

Methods

Twenty-eight members of the University of Massachusetts and Amherst College men's crew teams volunteered as subjects. Prior to testing, subjects read and signed an informed consent document. To avoid the possibility that residual fatigue from a previous test could influence a later test, testing took place on 4 separate days.

Day 1

Measurements of stature and body mass were performed followed by an incremental continuous peak oxygen uptake ($\dot{V}O_{2peak}$) rowing test. Stature was measured by a stadiometer to the nearest millimeter, and body mass was determined by weighing on a beam balance scale sensitive to 0.1 kg. $\dot{V}O_{2peak}$ was assessed by an incremental, continuous rowing test using a rowing ergometer (Concept II, Morrisville, Vt.). The initial power output was 200 W, and workload was increased in 50-W increments every 2 min (Steinacker 1993). Cadence was maintained at 33 strokes·min^{-1} to simulate the stroke rate most commonly used by rowers during competition (Steinacker 1993). Feedback regarding power output and rowing cadence was provided to the subject by a digital display. The criterion for $\dot{V}O_{2peak}$ was the highest 20-s value observed during the rowing test. Within the 1st min following the $\dot{V}O_{2peak}$ test, a fingertip blood sample was obtained to determine the maximal blood lactate level (Jensen 1991).

Physiological measures of $\dot{V}O_2$ and carbon dioxide production were monitored during exercise at 20-s intervals (Horizon 2900 Metabolic Measurements Cart, Sensormedics, Anaheim, Calif). The oxygen and carbon dioxide analyzers were calibrated before and after each test with known gases. Calibration of the air flow rate for ventilatory measures was performed prior to each test using a 3-l calibrated syringe. In addition, the flow rate at near-maximal values (175–200 l·min^{-1}) was calibrated prior to the investigation using a Tissot tank.

Blood samples were obtained by fingertip puncture and collected in a heparinized 37 μl microcapillary tube. The sample was immediately placed into a microcentrifuge tube containing a cocktail (sodium fluoride and Triton X100, Sigma, St. Louis, Mo.) to lyse the cells and halt glycolysis (Van Handel, Bradley, and Troup, unpublished paper). Lactate analysis was performed by the use of a flurometric lactate analyzer (YSI 23L, Yellow Springs Instruments, Yellow Springs, Ohio). The analyzer was calibrated before each sample by use of known standards. Two trials on each sample were obtained and the average of the trials was used as the criterion value.

Day 2

Rowing gross efficiency was determined during 6 min of rowing in a moving-water tank. A total of 6 min of exercise was selected to approximate the duration of a 2000-m race. Tank rowing in moving water was chosen to simulate on water rowing because the movements and forces required are similar to those present in the shell on water. The water was kept moving at 2 m·s^{-1} by a motor-driven propeller placed on the upstream side of the oarsman. The actual rowing time was divided into two, 3-min bouts separated by 60 s of rest. The rest period was used to obtain a blood sample for the determination of lactate accumulation. Subjects were asked to row at an intensity approximately equal to the middle portion of a rowing race when power output is generally constant and rowing at this intensity is 90% or more of $\dot{V}O_{2peak}$ (Secher 1983; Steinacker 1993). To maintain a constant power output, feedback regarding the force exerted during each stroke and each 30-s cadence was provided to the subject by a visual monitor.

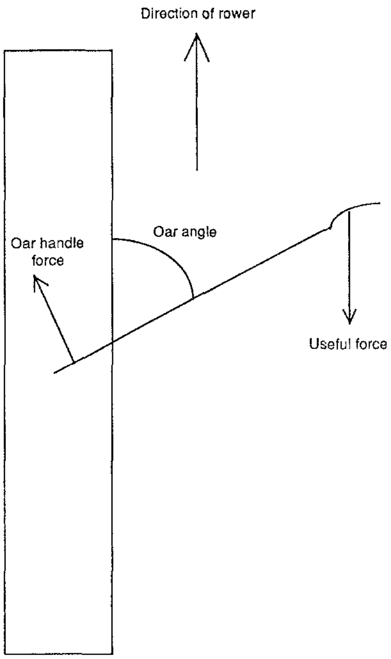

Fig. 1 Oar angles and force measured to determine mechanical power during 3 min of moving-water tank rowing. Measurements were determined by a potentiometer mounted on the oarlock and strain gauges mounted inboard from the oarlock (see text for description)

Figure 1 illustrates the oar angle and forces measured for the determination of rowing mechanical power. Oar angle during the stroke was determined by a potentiometer attached to the oar lock and calibrated before testing with a goniometer (Ishiko et al. 1983). Forces on the handle were assessed by placing two strain gauges on the oar parallel to the blade and two gauges perpendicular to the blade to form a four-arm Wheatstone bridge. The four strain gauges were mounted inboard from the oar lock to measure strain on the handle during a stroke. The strain perpendicular to the blade was calibrated by rotating the blade to horizontal, fastening it in place, and hanging a known load from the handle (Ishiko et al. 1983) to determine the force exerted at the blade. Positional and force data were collected at 60 Hz with a customized Basic computer program, using an analog to digital board (DT2801A, Data Translation, Marlboro, Mass.) and stored on a computer. The oar force and positional data were smoothed by employing a five-point moving average (Wood 1982). Work performed during one stroke was calculated by the integral of force with respect to displacement of the oar (Mason et al. 1988). The work performed during each stroke was summed to attain the total work performed during the sampling period and was described by the following equation:

$$\text{Work} = \int_{\phi_s}^{\phi_f} T d\phi$$

where: T = oar handle torque × sin (oar angle) (Fig. 1). Work was integrated from the starting position of the oar (ϕ_s) continuously through the exercise bout until the final oar position of the exercise bout (ϕ_f). Work in newton·meters was then converted to kilojoules (Åstrand and Rodahl 1986).

The initial non-linear rise in lactate observed at the beginning of exercise was minimized by allowing the rower to exercise at a constant power output for 3 min before blood collection. This workload was at a power output the subject felt was similar to the middle portion of a 2000-m race. It has been shown that if workload is kept constant and oxygen uptake ($\dot{V}O_2$) attains a constant level, net blood lactate accumulation increases linearly (di Prampero et al. 1971; Margaria et al. 1963). Blood lactate accumulation may then be used to account for anaerobic energy production (Cerretelli and Binzoni 1990; di Prampero et al. 1971; Margaria et al. 1963). Because lactate was measured after the initial rise at the onset of exercise, the total accumulation of lactate was decreased. However, this method provided for a linear accumulation of lactate during exercise because $\dot{V}O_2$ was allowed to attain a constant level (di Prampero 1981).

Blood samples were obtained from the fingertip during the interruption of exercise (lactate 1) and following completion of the second 3-min exercise bout (lactate 2). Samples were obtained immediately following exercise to minimize lactate clearance during recovery from exercise. In using blood lactate accumulation to estimate the energy cost of anaerobic metabolism, lactate cleared from the body during exercise is assumed to be accounted for by aerobic metabolism. Total energy cost is therefore the summation of oxygen equivalent of blood lactate accumulation and aerobic metabolism (di Prampero 1981). To estimate the cost of anaerobic energy transformation the aerobic equivalent of lactate has been determined to be the ratio of change in energy expenditure per unit time (when $\dot{V}O_2$ attains a constant level) to the change in lactate accumulated during that time (di Prampero 1981). By this method 1 $\mathrm{mmol \cdot l^{-1}}$ lactate has been estimated by regression to be equivalent to 3 $\mathrm{ml \cdot kg^{-1}}$ oxygen (Cerretelli and Binzoni 1990; di Prampero 1981; di Prampero et al. 1971; Margaria et al. 1963). The oxygen equivalent of blood lactate in $\mathrm{ml \cdot kg^{-1}}$ of oxygen was then added to the measured aerobic cost to determine gross efficiency. Gross efficiency was equal to the work performed during 3 min of rowing divided by the total energy cost in kJ (oxygen equivalent of accumulated blood lactate added to the $\dot{V}O_2$ measured during tank rowing).

Day 3

Knee extension leg strength was assessed using an isokinetic dynamometer (Biodex, Shilley, N.Y.) for each leg individually and both legs simultaneously. Although this motion does not include hip extension present in the drive part of the rowing stroke, knee extension is a significant part of the drive phase. The subject was seated with the lower legs hanging free and the thighs strapped to a seat for stabilization. The lower leg(s) were attached to the torque arm by a strap and pad(s) proximal to the ankle. Arms were folded across the torso to limit involvement of the upper body during the leg movement.

The test was preceded by five submaximal knee flexion-extension movements as a warm-up. The strength measure consisted of three maximal knee extension movements at a speed of 2.1 $\mathrm{rad \cdot s^{-1}}$, beginning with the knee flexed at approximately 1.3 rad and moved through full extension (Pyke et al. 1979). To minimize an order effect of learning and/or fatigue during testing, the order of leg testing (left or right) was systematically rotated for each new subject.

The criterion measure for leg strength was the peak isokinetic torque for each leg individually (left leg or inboard being closest to the oar during rowing and outboard, or right leg, being furthest from the oar) and both legs simultaneously (combined leg strength). Peak isokinetic torque was defined as the mean of peak torque values observed during each set of trials.

Day 4

A simulated rowing race (USRA race) was performed using a rowing ergometer according to United States Rowing Association guidelines (USRA 1990). The distance of the simulated race was 2000 m, with the goal being to complete the required distance in the shortest time period. The criterion measure was the total time required to complete the simulated race.

Thirty minutes after the USRA race, the USRA 6-min bench pull test (USRA 1990) was administered with the subject lying in the prone position on top of a bench with arms hanging down on both sides of the bench. The height of the bench was adjusted to allow the subject to maintain contact with a 41-kg barbell. On the start command, the subject pulled the barbell from the floor up to touch the bottom of the bench and returned it to the starting position to complete one repetition. During the test, the chest and legs remained in contact with the bench. To qualify as a repetition, the bar must have contacted the bench and could contact the floor. The criterion standard was the maximum number of repetitions that were satisfactorily completed in the 6-min time span.

Statistical analysis

The relationship of the physiological factors to rowing mechanical power and rowing gross efficiency were assessed by bivariate correlation. The variables associated with rowing gross efficiency and rowing mechanical power ($n = 21$) were used to predict gross efficiency and rowing mechanical power by forward stepwise regression analysis (Tabachnick and Fidell 1983). The ability of the independent variables to predict gross efficiency and rowing mechanical power was assessed by cross-validation with a hold-out subset of seven oarsmen for each equation (Efron and Gong 1983; Jensen and Kline 1994; Tabachnick and Fidell 1983).

Due to the small total number of subjects, multiple regression using the resampling cross-validation technique was used to predict rowing power and gross efficiency. Resampling cross-validation has been proposed as a means to extract information that cannot be readily and/or reliably accessed with a limited number of subjects (Efron and Gong 1983; Jensen and Kline 1994).

Results

Characteristics of the 28 subjects are displayed in Table 1. The subjects included members of the lightweight

Table 1 Selected physical characteristics of the subjects ($n = 28$)

Variable	Mean	SD	Min	Max
Height (m)	1.85	0.042	1.77	1.92
Body mass (kg)	78.9	6.78	67.0	90.0
$\dot{V}O_{2\mathrm{peak}}$ ($\mathrm{l \cdot min^{-1}}$)	5.26	0.460	4.56	6.15
$\dot{V}O_{2\mathrm{peak}}$ ($\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$)	66.9	4.92	56.2	77.3
$\dot{V}O_{2\mathrm{peak}}$ ($\mathrm{ml \cdot kg^{-2/3} \cdot min^{-1}}$)	286.3	91.21	244.9	320.8
Outboard leg strength (kg)	14.4	2.04	10.1	18.5
Inboard leg strength (kg)	14.1	1.93	11.0	18.4
Combined leg strength (kg)	23.7	3.52	14.8	20.9
USRA race (s)	411.0	13.75	379.0	434.0
USRA bench pull	104.8	26.75	53.0	154.0
Maximal lactate ($\mathrm{mmol \cdot l^{-1}}$)	13.9	1.74	10.1	16.4
Pre-tank lactate ($\mathrm{mmol \cdot l^{-1}}$)	7.3	1.79	2.6	10.7
Post-tank lactate ($\mathrm{mmol \cdot l^{-1}}$)	11.1	2.06	7.4	15.6
Accumulated blood lactate ($\mathrm{mmol \cdot l^{-1}}$)	3.8	1.63	1.3	7.5
Total energy cost (kJ)	324.8	34.45	269.6	383.9
Fractional utilization of O_2 (%)	91.1	9.30	73.9	110.1
Rowing mechanical power (W)	483.4	34.75	424.4	557.1
Gross rowing efficiency (%)	24.4	2.60	19.5	29.0

(body mass ≤ 72.5 kg) and open (no body mass restriction) crews. Six of the subjects were novice oarsmen (less than 1 year of rowing experience) and 22 of the subjects were varsity oarsmen (1–4 years of rowing experience).

Mean (SD) power output sustained during the 3 min of tank rowing was 483.4 (34.76) W. This value did not differ with respect to experience [experienced = 487.2 (34.87) W; inexperienced = 469.4 (33.57) W], side rowed [starboard = 481.3 (37.75) W; port = 485.7 (32.38) W], or weight class [lightweight = 468.3 (26.94) W; open = 487.4 (36.06) W; $P > 0.05$]. The gross efficiency attained by the current subjects was 24.4 (2.60)%. Similar to power output, gross efficiency did not differ based on experience [experienced = 24.6 (2.56)%; inexperienced = 23.5 (2.98)%], side rowed [starboard = 24.6 (2.18); port = 24.1 (3.15)%], or weight class [lightweight = 25.1 (0.98)%; open = 24.2 (2.91)%; $P > 0.05$]. Because there were no differences for rowing efficiency and mechanical power based on experience, side rowed, or weight class, subjects were combined in one group for subsequent analyses. In absolute terms, $\dot{V}O_{2\text{peak}}$ was 5.26 (0.46) $\text{l} \cdot \text{min}^{-1}$. The mean (SD) value for maximal blood lactate was 13.9 (1.74) $\text{mmol} \cdot \text{l}^{-1}$. The $\dot{V}O_2$ during the tank rowing was 4.78 (0.525) $\text{l} \cdot \text{min}^{-1}$; this value was equivalent to a fractional utilization of oxygen peak of 91.1 (9.30) %. In addition, the blood lactate following 6 min of tank rowing was 83.8 (16.98)% of the lactate attained during the maximal test – a further indication of high-intensity exercise.

There were no significant correlations between rowing gross efficiency and any of the independent variables ($P > 0.05$; Table 2). This indicates that the independent variables would be unable to predict rowing efficiency during near-maximal tank rowing.

There were significant correlations between the measures of leg strength and the rate of power production during tank rowing ($P < 0.05$). The highest correlation was between inboard leg (IL) strength and rowing mechanical power ($r = 0.63$, $P < 0.01$). Outboard leg (OL) strength ($r = 0.45$), and combined leg strength ($r = 0.45$) were also correlated to rowing mechanical power ($P < 0.05$). The only other variable in the current investigation that exhibited a significant correlation to tank rowing mechanical power was the time to complete the USRA simulated 2000-m race ($r = -0.52$, $P < 0.05$).

IL strength was the first variable entering the equation in 12 of the 15 regression equations. Combined leg strength entered on the first step for two equations and USRA race entered first for one equation. When combined leg strength and USRA race were excluded from entering those three equations, IL strength was the first variable entering the regression for all 15 random samples producing a significant multiple R ranging from $R = 0.54$ to $R = 0.80$ ($P < 0.05$). Blood lactate following a $\dot{V}O_{2\text{peak}}$ test (MBL) entered on the second step in 9 of the 15 equations. When both variables were forced to enter the equation a significant multiple R (range 0.61 to 0.86; $P < 0.05$) was attained for all 15 samples [$\bar{x} = 0.72$, 95% confidence interval (CI_{95}) = 0.68 to 0.76]. The range of standard error of estimate (SEM) for the 15 equations was from 18.1 to 29.9 W ($\bar{x} = 25.7$, CI_{95} = 23.8 to 27.7 W) or 5.3 (0.77)% of the criterion value.

The use of all 28 subjects in a prediction model should result in an equation that resembles the mean results of the resampling technique. Indeed the multiple R and SEM when IL strength and MBL were forced variables was $R = 0.69$ and SEM = 26.1 W. These values are similar to the mean values of $R = 0.72$ and SEM = 25.7 W attained from the resampling technique (see Table 3). Furthermore, the equation obtained when using all subject data Power = 392.287 + [11.77 × (IL-strength)] – (5.589 × MBL), was similar to the mean equation that resulted from the resampling analysis (see Table 3). However, because this method eliminates the

Table 2 Correlations of gross rowing efficiency and rowing mechanical power to independent variables ($n = 28$). Correlation of gross rowing efficiency to rowing mechnical power was $r = 0.391$

Independent variable	Gross efficiency	Rowing mechanical power
Height (m)	– 0.082	0.399
Body mass (kg)	– 0.289	0.350
$\dot{V}O_{2\text{peak}}$ ($\text{l} \cdot \text{min}^{-1}$)	– 0.331	0.176
$\dot{V}O_{2\text{peak}}$ ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	– 0.041	– 0.206
$\dot{V}O_{2\text{peak}}$ ($\text{ml} \cdot \text{kg}^{-2/3} \cdot \text{min}^{-1}$)	– 0.176	– 0.072
Outboard leg strength (kg)	– 0.191	0.450*
Inboard leg strength (kg)	– 0.081	0.631*
Combined leg strength (kg)	– 0.185	0.450*
USRA race (s)	0.170	– 0.519*
USRA bench pull	0.065	0.210
Maximal lactate ($\text{mmol} \cdot \text{l}^{-1}$)	– 0.097	– 0.227

*Significant correlation ($P < 0.05$)

Table 3 Summary statistics for predicting rowing mechanical power from the 15 regression equations and cross-validations obtained by the bootstrap technique (*SEM* standard error of estimate)

	Mean	SD	Minimum	Maximum
Development				
Multiple R	0.72	0.071	0.61	0.85
SEM	25.74	3.593	18.05	29.85
Beta coefficients				
Inboard leg strength	1.033	0.0850	0.865	1.197
Maximal blood lactate	– 4.507	1.338	– 7.432	– 2.813
Constant	364.511	21.512	309.729	399.960
Validation				
Correlation	0.61	0.232	0.14	0.97
SEM	25.40	10.316	7.95	38.87
Mean difference	3.19	14.599	– 27.61	22.38
t-value	0.702	1.485	– 2.07	2.81

possibility of cross-validation and is further limited by the small sample size and poor statistical power, its use is not recommended (Efron and Gong 1983; Jensen and Kline 1994).

A hold-out group of seven individuals was used to cross-validate the corresponding regression equation for each of the 15 random samples selected from the pool of 28 subjects. The results of the cross-validation correlations were similar to those obtained for the original equations (see Table 3). The cross-validation equations ranged from $R = 0.14$ to 0.97 ($\bar{x} = 0.61$, $CI_{95} = 0.48$ to 0.74). The range of SEM was from 8.0 to 38.9 W ($\bar{x} = 25.4$, $CI_{95} = 19.66$ to 31.08 W).

Discussion

A major finding of the current study was the inability to correlate gross efficiency during rowing with any of the independent measures. The lack of correlation suggests that rowing performance and gross efficiency are unrelated. This is in contrast to literature relating performance to exercise gross efficiency during cycling (Malhotra et al. 1984).

The reason for the inability to correlate performance measures to rowing efficiency is unknown, but several possibilities related to the specific nature of rowing may shed light on the matter. The duration of a 2000-m rowing race is much shorter (approximately 6–8 min; Steinacker 1993) than that of the cycling performance times studied (16–120 min; Malhotra et al. 1984). This difference in duration of exercise may mean that a major factor in gross efficiency, the rate of energy cost for the activity, is of little importance and thus does not explain the variance in rowing efficiency.

Another possible explanation for the inability to predict rowing efficiency may be related to the intensity of exercise. Most investigations of exercise gross efficiency are conducted at intensity levels of 70% $\dot{V}O_{2peak}$ or less, or below the level of net lactate accumulation (Malhotra et al. 1984). Oarsmen, however, typically maintain an energy output at a rate greater than 90% $\dot{V}O_{2peak}$ for the entire race, while runners and cyclists typically avoid this level of exercise until the final portion of the race. Subjects in the current study maintained a mean (SD) fractional utilization of oxygen of 91.1 (9.30)% $\dot{V}O_{2peak}$ during the tank rowing test. In addition, they displayed a net accumulation of blood lactate that was 83.8 (17)% of lactate attained during a maximal test. It may be that exercise at a high intensity or the inclusion of the oxygen equivalent of lactate make the determination of gross efficiency, as it is commonly defined, impossible.

The production of force during rowing is characterized by an oscillating force output with peak forces occurring during the drive portion of the stroke cycle (Dal Monte and Komor 1989). The timing of peak force production is extremely important in rowing, because poorly timed forces compromise velocity and result in decreased performance (Dal Monte and Komor 1989). Furthermore, in rowing there are also continuous variations in the velocity of the shell due to the pulsatile actions of the rowing stroke and movement of the athlete within the shell. These variations result in a decrease of efficiency much greater than those exhibited in cycling. Because of these factors, specific to rowing, individual differences in rowing gross efficiency may not be present to the same extent as in cycling efficiency. Therefore, although gross efficiency is commonly used to compare many other activities, it may not be the most appropriate method to study rowing performance.

Although the prediction of gross efficiency was not possible in the current investigation the prediction of mechanical power production during tank rowing was possible using IL strength and maximal blood lactate as the independent variables. The relationship of leg strength to rowing mechanical power is in agreement with literature that has shown stronger rowers, particularly those with high leg strength, perform better (Hagerman et al. 1972; Pyke et al. 1979). A probable reason for this finding is that for skilled rowers the major portion of the propulsive phase takes place during the leg drive (Asami et al. 1985; Dal Monte and Komor 1989; Schneider et al. 1978). In addition, the highest resistance, and therefore force requirement, is at the beginning of the drive, when the legs are the major source of propulsion (Asami et al. 1985; Dal Monte and Komor 1989; Nelson and Widule 1983). This phase of the stroke is also when the water and/or shell are moving at the slowest speed and therefore require a greater force to initiate motion. As the oar passes a point perpendicular to the direction of travel and the legs play less of a factor, the force on the oar decreases (Dal Monte and Komor 1989; Ishiko et al. 1983; Nelson and Widule 1983). This would indicate less need for strength when the trunk and arms are moving the oar.

It is possible that the degree of leg strength may also have been a factor in determining the entrance of the variables related to rowing mechanical power. Examination of Table 1 shows that the mean value for IL strength was slightly less than OL strength. Theoretically, high leg strength would be required to maintain a high level of rowing mechanical power. Therefore, lower leg strength of IL would explain additional variability of rowing mechanical power because there would be a greater variation at lower levels. In other words, those values above some specific level would not differentiate between individuals, thus indicating the existence of a strength threshold, that when exceeded would eliminate leg strength as a predictor of rowing mechanical power. Indeed, Steinacker (1993) has proposed just such a threshold for the contribution of strength to rowing performance.

The entrance of blood lactate as a predictor of rowing mechanical power is not unexpected because approximately 33% of the energy required during competitive rowing is transformed by anaerobic means (Steinacker 1993). However, because an ability to attain high levels of blood lactate should indicate the capacity to transform more energy anaerobically, a positive correlation with power production would be expected. On the contrary, maximal blood lactate was negatively correlated with rowing mechanical power.

An explanation of the negative correlation has been suggested by the findings of Jensen (1991), who showed that peak lactate was correlated to a decrease in power during 6 min of ergometer rowing. It was stated that "muscle fatigue and a decrease in power during rowing are influenced by blood lactate concentration." Conversely, an individual who did not reach a high blood lactate level should be better able to maintain a higher power output. Support of this theory has been provided by the recent findings of Hogan et al. (1995), indicating that when arterial and muscular lactate concentration is increased development of muscular tension is decreased.

A reason for the lack of relationship between rowing mechanical power and $\dot{V}O_{2\mathrm{peak}}$ may be that during rowing a major factor in the expression of power [(force × distance) ÷ time] is the degree of force applied. The force production required to complete one repetition in rowing is higher than that of cycling; thus high strength may be necessary to obtain high power levels during rowing. Indeed leg strength is the first variable to enter the equation to predict rowing mechanical power. It is possible that the need for high levels of force production, especially by the legs, override a requirement of high aerobic capacity. The findings of Pyke and colleagues (1979) indicating that rowing performance was more highly correlated to isokinetic leg strength ($r = 0.82$) than to $\dot{V}O_{2\mathrm{peak}}$ ($r = 0.63$) would support this theory.

Finally, it may be possible that although $\dot{V}O_{2\mathrm{peak}}$ is an important factor in rowing performance there may be a threshold above which this importance is diminished. This would be analogous to the "critical value" above which strength and anaerobic capacity need not be increased as suggested by Steinacker (1993). Hagerman (1984) reported serial data of three subjects (absolute $\dot{V}O_{2\mathrm{peak}}$ approximately $6.0\ \mathrm{l \cdot min^{-1}}$) who were tested repeatedly over the course of 8 years, and demonstrated a gradual increase in power production despite the fact that $\dot{V}O_{2\mathrm{peak}}$ remained the same. There is additional support for this theory outside the field of rowing. Kearney and Van Handel (1989) state that there is little difference in efficiency between elite and sub-elite groups, but marked differences for the trained and untrained (i.e. those of vastly different aerobic capacities). It is possible that the same may be true for power production and that the threshold for $\dot{V}O_{2\mathrm{peak}}$ was surpassed by the subjects of the current investigation. It should be emphasized that the lowest $\dot{V}O_{2\mathrm{peak}}$ attained by any of the subjects was $4.6\ \mathrm{l \cdot min^{-1}}$, or $56.2\ \mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$, a level indicative of a trained state for non-elite athletes (Åstrand and Rodahl 1986). Expressed in the manner suggested by Secher (1983) the lowest $\dot{V}O_{2\mathrm{peak}}$ for the current subjects was $244.6\ \mathrm{ml \cdot kg^{-2/3} \cdot min^{-1}}$, a value only 15% lower than the mean of $290\ \mathrm{ml \cdot kg^{-2/3} \cdot min^{-1}}$ for elite oarsmen (Secher 1983). Therefore, the necessary $\dot{V}O_{2\mathrm{peak}}$ may have been attained eliminating it as a predictor of power.

In conclusion, the present investigation has shown that prediction of near-maximal rowing gross efficiency is not possible using measures of strength, power, aerobic, and anaerobic capacities as independent variables. IL strength and blood lactate measured following a rowing $\dot{V}O_{2\mathrm{peak}}$ test emerged as predictors of rowing mechanical power using a resampling analysis of 15 regression equations. Cross-validation of these equations with a hold-out group yielded correlations and SEM similar to those attained during the development of the equations.

Physiologically, the finding that leg strength is positively related and MBL negatively related to rowing mechanical power is not unexpected. High levels of leg strength are necessary to overcome water resistance to oar movement during the drive phase of the stroke. Because leg drive is an initiator of each stroke, leg strength is required to maintain power through the duration of the exercise bout. High blood lactate levels have been related to muscle fatigue and a consequent decrease in mechanical power. Thus, avoiding high blood lactate levels early in exercise should enable an individual to maintain a higher power output resulting in improved performance and a faster race time. With regard to training, the findings of the current study suggest a rower should emphasize training that increases leg strength and results in the ability to minimize high blood lactate levels.

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